

# Higgs Masses and More in the Complex MSSM with FeynHiggs

T. Hahn<sup>1a</sup>, S. Heinemeyer<sup>2</sup>, W. Hollik<sup>1</sup>, H. Rzehak<sup>3b</sup>, G. Weiglein<sup>4</sup>

<sup>1</sup> Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany

<sup>2</sup> Instituto de Fisica de Cantabria (CSIC-UC), Santander, Spain

<sup>3</sup> Paul Scherrer Institut, Würenlingen und Villigen, CH-5232 Villigen PSI, Switzerland

<sup>4</sup> IPPP, University of Durham, Durham DH1 3LE, UK

**Abstract.** We present the latest version 2.6 of FeynHiggs, a program for computing MSSM Higgs-boson masses and related observables, such as mixing angles, branching ratios, and couplings, including state-of-the-art higher-order contributions. The most important new feature is the inclusion of the fully complex  $\mathcal{O}(\alpha_t \alpha_s)$  two-loop corrections, which enables FeynHiggs to give the most precise Higgs-mass evaluation in the complex MSSM in the Feynman-diagrammatic approach to date.

**PACS.** 12.60.Jv Supersymmetric models – 14.80.Cp Non-standard-model Higgs bosons

## 1 Complex Parameters in the MSSM Higgs Sector

The Higgs sector of the Minimal Supersymmetric Standard Model with complex parameters (cMSSM) consists of two Higgs doublets

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad (1)$$

$$H_2 = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix} \quad (2)$$

which form the following Higgs potential

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - (m_{12}^2 \varepsilon_{\alpha\beta} H_1^\alpha H_2^\beta + \text{h.c.}) + \frac{g_1^2 + g_2^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g_2^2}{2} |H_1 \bar{H}_2|^2. \quad (3)$$

The Higgs potential contains two complex phases  $\xi$ ,  $\arg(m_{12}^2)$ . The phase  $\arg(m_{12}^2)$  can be rotated away [1,2] and, at tree level,  $\xi$  has to vanish in order to fulfill the minimum condition of the Higgs potential, so there is no CP-violation at tree level and the spectrum contains five states of definite CP-parity:  $h$ ,  $H$ ,  $A$ ,  $H^\pm$ . In the following we review the inclusion of higher-order corrections to Higgs-boson masses and more into the code FeynHiggs [3,4,5,6].

CP-violating effects are induced by complex parameters that enter via loop corrections: the Higgsino mass parameter  $\mu$ , the trilinear couplings  $A_{t,b,\tau}$ , and the gaugino mass parameters  $M_{1,2,3}$ . They yield  $\hat{\Sigma}_{hA}$ ,

$\hat{\Sigma}_{hA} \neq 0$  and induce mixing between  $h$ ,  $H$ , and  $A$  [7]. The Higgs mass matrix has the form

$$\mathbf{M}^2 = \begin{pmatrix} q^2 - m_h^2 + \hat{\Sigma}_{hh} & \hat{\Sigma}_{hH} & \hat{\Sigma}_{hA} \\ \hat{\Sigma}_{Hh} & q^2 - m_H^2 + \hat{\Sigma}_{HH} & \hat{\Sigma}_{HA} \\ \hat{\Sigma}_{Ah} & \hat{\Sigma}_{AH} & q^2 - m_A^2 + \hat{\Sigma}_{AA} \end{pmatrix}, \quad (4)$$

where  $m_{h,H,A}$  denote the tree-level Higgs masses, and it should be noted that in general  $\mathbf{M}^2$  is symmetric but not Hermitian. In the approximation of vanishing external momentum ( $q^2 = 0$ ), one can obtain the higher-order corrected mass eigenstates via a unitary transformation from the tree-level states:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} h \\ H \\ A \end{pmatrix}. \quad (5)$$

## 2 Higgs-boson self-energy corrections in FeynHiggs

### 2.1 Higgs-boson masses

The following contributions to the mass matrix and the charged-Higgs-boson self-energy are taken into account:

$$\begin{pmatrix} q^2 - m_h^2 + \hat{\Sigma}_{hh}^{(123)} & \hat{\Sigma}_{hH}^{(123)} & \hat{\Sigma}_{hA}^{(13)} \\ \hat{\Sigma}_{Hh}^{(123)} & q^2 - m_H^2 + \hat{\Sigma}_{HH}^{(123)} & \hat{\Sigma}_{HA}^{(13)} \\ \hat{\Sigma}_{Ah}^{(13)} & \hat{\Sigma}_{AH}^{(13)} & q^2 - m_A^2 + \hat{\Sigma}_{AA}^{(13)} \end{pmatrix}, \quad (6)$$

$\hat{\Sigma}_{H+H-}^{(13)}$

<sup>a</sup> e-mail: hahn@feynarts.de

<sup>b</sup> e-mail: Heidi.Rzehak@psi.ch

① Leading  $\mathcal{O}(\alpha_t \alpha_s)$  cMSSM two-loop corrections [8].

- ② Leading  $\mathcal{O}(\alpha_t^2)$  and subleading  $\mathcal{O}(\alpha_b\alpha_s, \alpha_t\alpha_b, \alpha_b^2)$  two-loop corrections evaluated in the MSSM with real parameters (rMSSM), where the phases are included only partially [9, 10, 11].
- ③ Full one-loop evaluation (all phases,  $q^2$  dependence) [6] and leading non-minimal flavour-violating (NMFV) corrections [12].

FeynHiggs performs a numerical search for the complex roots of  $\det \mathbf{M}^2(q^2)$  which are denoted as  $\mathcal{M}_{h_i}^2$ ,  $i = 1 \dots 3$ . A decomposition can be performed,

$$\mathcal{M}^2 = M^2 - iM\Gamma, \quad (7)$$

where  $M$  is the mass of the particle and  $\Gamma$  its width. We then define the loop-corrected masses according to

$$M_{h_1} \leq M_{h_2} \leq M_{h_3}. \quad (8)$$

The Higgs masses are thus determined as the real parts of the complex poles of the propagator. Complex contributions to the Higgs mass matrix (from  $\text{Im } \hat{\Sigma}$ ) are taken into account [6, 13]. The diagonalization routines are available as a stand-alone package from the Web site [www.feynarts.de/diag](http://www.feynarts.de/diag) [14].

## 2.2 Two-loop corrections in the complex MSSM

Including the phase dependence, the complete one-loop [6] and the two-loop contribution of  $\mathcal{O}(\alpha_t\alpha_s)$  [8] to the Higgs self-energies are taken into account. Within the Higgs sector, the parameters have to be defined up to  $\mathcal{O}(\alpha_t\alpha_s)$ . The masses of the charged Higgs boson, the  $Z$ -boson, as well as the  $W$ -boson are defined as pole masses,

$$\delta M_X^{(i)} = \text{Re} \Sigma_{XX}^{(i)}(M_X^2) \text{ with } X = \{H^\pm, W, Z\}, \quad (9)$$

with  $(i)$  denoting the loop order. Furthermore, it is required that there be no shift of the minimum of the Higgs potential which is fixing the tadpole parameters,

$$\delta t_\phi^{(i)} = -T_\phi^{(i)} \quad \text{with } \phi = \{h, H, A\}. \quad (10)$$

The  $Z$ -factors and  $\tan\beta$  are defined within the  $\overline{\text{DR}}$ -scheme [15, 16].

The parameters of the top sector have to be defined at one-loop level. The top-quark mass and the top-squark masses are fixed by an on-shell condition and the mixing angle and the corresponding phase by

$$\text{Re} \hat{\Sigma}_{\tilde{t}_{12}}(m_{\tilde{t}_1}^2) + \text{Re} \hat{\Sigma}_{\tilde{t}_{12}}(m_{\tilde{t}_2}^2) = 0, \quad (11)$$

generalizing the renormalization conditions imposed in [17] for the use of complex parameters.

To extract the relevant terms at two-loop order we used the approximation of vanishing external momenta and vanishing electroweak gauge couplings in the evaluation of all two-loop diagrams including those needed for calculating the two-loop counterterms.

A new flag in FeynHiggs (see Sec. 6.2 below) controls the treatment of phases in the part of the two-loop corrections known only in the rMSSM so far. The following options are possible:

- all corrections:  $\mathcal{O}(\alpha_t\alpha_s, \alpha_b\alpha_s, \alpha_t^2, \alpha_t\alpha_b, \alpha_b^2)$  in the rMSSM,
- only the cMSSM  $\mathcal{O}(\alpha_t\alpha_s)$  corrections,
- the cMSSM  $\mathcal{O}(\alpha_t\alpha_s)$  corrections combined with the remaining corrections in the rMSSM, truncated in the phases,
- the cMSSM  $\mathcal{O}(\alpha_t\alpha_s)$  corrections combined with the remaining corrections in the rMSSM, interpolated in the phases [default].

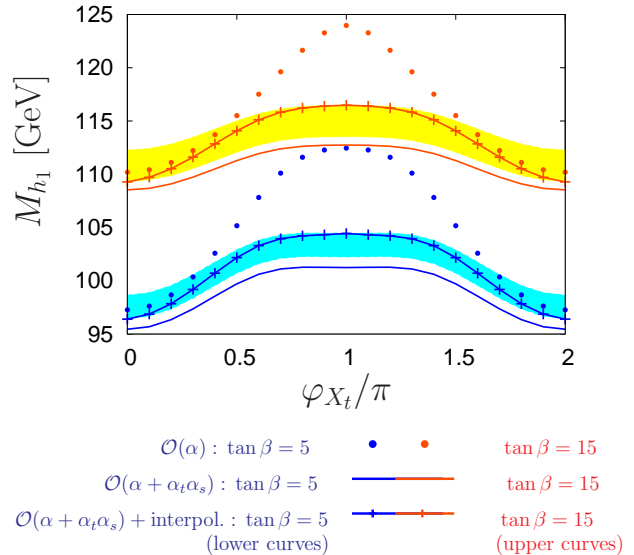
FeynHiggs thus not only has the most precise evaluation of the Higgs masses in the cMSSM available to date (using the Feynman-diagrammatic approach), but also a method to obtain a reasonably objective estimate of the uncertainties due to the rMSSM-only parts.

Implementing the  $\mathcal{O}(\alpha_t\alpha_s)$  cMSSM corrections in FeynHiggs was a major piece of work. The amplitudes could be shrunk from 38 MB to less than 1.5 MB, mainly by abbreviating techniques and exploiting the unitarity of the sfermion mixing matrices. The compile time is about 3 min (up from 45 sec in FeynHiggs 2.5) and the run time is 28 msec per parameter point (up from 27 msec in FeynHiggs 2.5). These figures show that the full cMSSM evaluation is actually usable in everyday life.

As a numerical example we show in Fig. 1 the dependence of  $M_{h_1}$  on the phase of the top-squark mixing,  $X_t = A_t - \mu^* \cot\beta$ . The plot shows the one-loop-corrected Higgs mass  $M_{h_1}$  as dotted curve. The drawn-through curve depicts the Higgs mass  $M_{h_1}$  including contributions of  $\mathcal{O}(\alpha_t\alpha_s)$ . The boundaries of the bands are calculated in the following way:

$$M_{h_1}^{\text{low}}(\varphi_{X_t}) = M_{h_1}^{\text{corr.}}(\varphi_{X_t}) + \Delta M_{h_1}(\varphi_{X_t} = 0), \quad (12)$$

$$M_{h_1}^{\text{up}}(\varphi_{X_t}) = M_{h_1}^{\text{corr.}}(\varphi_{X_t}) + \Delta M_{h_1}(\varphi_{X_t} = \pi), \quad (13)$$



**Fig. 1.** The lightest cMSSM Higgs-boson mass as a function of  $\varphi_{X_t}$  at the one- and two-loop level (see text). The other parameters are:  $M_{\text{SUSY}} = M_3 = M_2 = 500$  GeV,  $M_1 = 250$  GeV,  $\mu = 1000$  GeV,  $M_{H^\pm} = 150$  GeV,  $|X_t| = 700$  GeV.

where  $M_{h_1}^{\text{low}}$  and  $M_{h_1}^{\text{up}}$  respectively give the lower and the upper boundary of the bands for

$$\Delta M_{h_1}(\varphi_{X_t} = 0) \leq \Delta M_{h_1}(\varphi_{X_t} = \pi). \quad (14)$$

If, unlike in our numerical example, Eq. (14) does not hold,  $M_{h_1}^{\text{low}}$  and  $M_{h_1}^{\text{up}}$  have to be interchanged in Eqs. (12) and (13).

$M_{h_1}^{\text{corr.}}$  are the values for  $M_{h_1}$  including the full one-loop and the  $\mathcal{O}(\alpha_t \alpha_s)$  corrections with the full phase dependence.  $\Delta M_{h_1}$  gives the size of the contributions that are only known for real parameters, namely those of  $\mathcal{O}(\alpha_t^2, \alpha_b \alpha_s, \alpha_t \alpha_b, \alpha_b^2)$ .

The crossed curve shows  $M_{h_1}$ , taking into account the  $\mathcal{O}(\alpha_t \alpha_s)$  contributions and interpolating  $\Delta M_{h_1}$ , i.e. the corrections of  $\mathcal{O}(\alpha_t^2, \alpha_b \alpha_s, \alpha_t \alpha_b, \alpha_b^2)$ . The fact that these crossed curves lie between the lower and the upper boundaries of the corresponding band shows that the interpolation procedure is working well.

For the parameters chosen here (especially due to a relatively small value of  $M_{H^\pm}$ ) the  $\mathcal{O}(\alpha_t \alpha_s)$  contributions decrease the phase dependence. As known from the rMSSM [4], they cause a shift of  $M_{h_1}$  towards lower values with respect to the one-loop corrected mass, the  $\mathcal{O}(\alpha_t^2, \alpha_b \alpha_s, \alpha_t \alpha_b, \alpha_b^2)$  corrections increase again the size of the  $M_{h_1}$ .

### 2.3 Mixing of the Higgs bosons

FeynHiggs returns two different ‘mixing’ matrices.

- **UHiggs** is a ‘true’ mixing matrix in the sense of being unitary and hence preserving probabilities. When applying effective couplings for internal Higgs bosons, this matrix must be used. It should be noted that to obtain a unitary matrix, it is mathematically a necessity that  $\mathbf{M}^2$  has no imaginary parts – making it Hermitian. This of course constrains the achievable quality of approximation.
- **ZHiggs** is a matrix of Z-factors. It guarantees on-shell properties for external Higgs bosons [6], see Eq. (18) below.

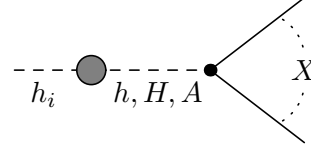
It is important to understand that **ZHiggs** and **UHiggs** are two objects with physically and mathematically distinct properties. Neither is universally ‘better’ than the other.

**UHiggs** can be computed in two approximations:

- $q^2$  on-shell:  $\hat{\Sigma}_{ii}(q^2 = m_i^2)$ ,  $\hat{\Sigma}_{ij}(q^2 = \frac{1}{2}(m_i^2 + m_j^2))$ .
- $q^2 = 0$  (see Eq. (5)). **UHiggs** coincides with **ZHiggs** in this limit and corresponds to the effective potential approach. In the absence of CP-violating effects, i.e.  $2 \times 2$  mixing only, this is identical to the  $\alpha_{\text{eff}}$  description [18].

**ZHiggs** is engineered to deliver the correct on-shell properties of an external Higgs boson, but is not necessarily unitary [6]. The following picture shows the type of mixing contributions which appear in the decay of an external Higgs boson (the contributions from

mixing with the Goldstone boson and with the longitudinal component of the Z-boson are numerically small and hence neglected):



Disregarding possible permutations for the moment (but see below), the corresponding combination of amplitudes are

$$\Gamma_{h_1} = \sqrt{Z_h}(\Gamma_h + Z_{hH}\Gamma_H + Z_{hA}\Gamma_A) \quad (15)$$

$$\Gamma_{h_2} = \sqrt{Z_H}(Z_{Hh}\Gamma_h + \Gamma_H + Z_{HA}\Gamma_A) \quad (16)$$

$$\Gamma_{h_3} = \sqrt{Z_A}(Z_{Ah}\Gamma_h + Z_{AH}\Gamma_H + \Gamma_A) \quad (17)$$

where

- $\Gamma_{h,H,A}$  is the amplitude for  $h, H, A \rightarrow X$ ,
- $\sqrt{Z_{h,H,A}}$  sets the residuum of the external Higgs bosons to 1,
- $Z_{hH}, Z_{hA}$  describe the transition  $h \rightarrow H, A$ , etc.

For convenience, the Z factors can be arranged in matrix form:

$$\mathbf{ZHiggs} = \begin{pmatrix} \sqrt{Z_h} & \sqrt{Z_h} Z_{hH} & \sqrt{Z_h} Z_{hA} \\ \sqrt{Z_H} Z_{Hh} & \sqrt{Z_H} & \sqrt{Z_H} Z_{HA} \\ \sqrt{Z_A} Z_{Ah} & \sqrt{Z_A} Z_{AH} & \sqrt{Z_A} \end{pmatrix}. \quad (18)$$

In this guise, **ZHiggs** can be used very much like **UHiggs** even though its theoretical origin is quite different. Reassuringly, **ZHiggs** and **UHiggs** coincide in the limit  $q^2 = 0$ .

The transition factors  $Z_{ij}$  involve both the tree-level mass  $m_i$  and the loop-corrected mass  $\mathcal{M}_i$  of each Higgs boson:

$$Z_{ij} = \frac{\hat{\Sigma}_{ik}(\mathcal{M}_i^2) \hat{\Sigma}_{jk}(\mathcal{M}_i^2) - \hat{\Sigma}_{ij}(\mathcal{M}_i^2) Y_{ij}}{Y_{ij} Y_{ik} - \hat{\Sigma}_{jk}^2(\mathcal{M}_i^2)}, \quad (19)$$

$$Y_{ij} = \mathcal{M}_i^2 - m_j^2 + \hat{\Sigma}_j(\mathcal{M}_i^2). \quad (20)$$

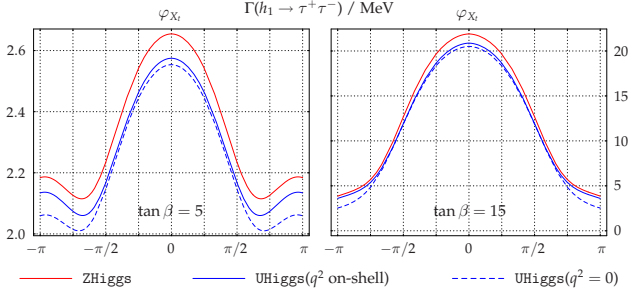
To compute  $Z_{ij}$  we thus have to make the connection between the ‘loop’ ( $h_1, h_2, h_3$ ) and the ‘tree’ ( $h, H, A$ ) states. Neither the zero-search nor the diagonalization procedure allow to do this in an unambiguous way. For example, level crossings may occur when searching for the zeros of  $\det \mathbf{M}^2$ .

The algorithm currently used by FeynHiggs is: compute **ZHiggs** and the associated masses  $\tilde{M}_i$  for all permutations  $\pi$  of Higgs states involved in the mixing and choose the one which minimizes

$$\sum_i |M_i - \tilde{M}_{\pi(i)}| + \sum_{i,j} |C_{ij} - \mathbf{ZHiggs}_{\pi(i)j}| \quad (21)$$

where  $C$  is the mixing matrix that comes out of the diagonalization of  $\mathbf{M}^2$  with  $q^2 = M_{h_2}^2$ , i.e. a by-product of the zero-search.

This is an empirical recipe, so the different dimensions of  $M$  and  $Z$  should not be taken very seriously.



**Fig. 2.** The decay width of the lightest Higgs boson to  $\tau$  leptons as a function of  $\varphi_{X_t}$  for  $\tan\beta = 5$  (left) and  $\tan\beta = 15$  (right). The other parameters are:  $M_{\text{SUSY}} = M_3 = M_2 = 500$  GeV,  $\mu = 1000$  GeV,  $M_{H^\pm} = 150$  GeV,  $X_t = 700 e^{i\varphi_{X_t}}$  GeV.

The permutation is decided in nearly all cases by the mass pattern. The  $|C - Z|$  term becomes relevant only for (almost) degenerate masses where it can tell e.g. the symmetric from the antisymmetric state.

The numerical effects of using the various mixing matrices in a physical amplitude are shown in Fig. 2. For the chosen parameters,  $\text{UHiggs}(q^2 \text{ on-shell})$  gives results closer to the full result than  $\text{UHiggs}(q^2 = 0)$ , with deviations at the few-percent level. For a detailed discussion see Ref. [6].

The mixing of the neutral Higgs bosons in the cMSSM has also been added to FeynArts [19]. A special version of the MSSM Model File [20], `HMix.mod`, provides two sets of appropriately mixed Higgs bosons:

$$\begin{aligned} - \text{S}[0, \{h\}] &= \sum_{i=1}^3 \text{UHiggs}[h, i] \text{S}[i], \text{ and} \\ - \text{S}[10, \{h\}] &= \sum_{i=1}^3 \text{ZHiggs}[h, i] \text{S}[i]. \end{aligned}$$

The latter is inserted only on external lines.

### 3 Benchmark Scenarios

FeynHiggs has long included Benchmark Scenarios [21] which are useful in the search for the MSSM Higgs bosons. The idea is to vary only  $M_A$  and  $\tan\beta$  and keep all other SUSY parameters fixed.

Constraints such as Cold Dark Matter (CDM) have been ignored in these scenarios. It might be desirable to investigate  $M_A$ - $\tan\beta$  planes in agreement with CDM and other external constraints, however (if the planes are derived in a GUT-based model, see Ref. [22] for a discussion).

For the Constrained MSSM (or mSUGRA) as candidate model, the CDM constraints turn out to be too severe, i.e. cut out almost all available parameter space. This is different in the NUHM (Non-universal Higgs-mass model) [23], where the assumption is that there is no unification of scalar fermion and scalar Higgs parameters at the GUT scale. As additional free parameters in this model one can choose  $M_A$  and  $\mu$ .

In Ref. [22] four  $M_A$ - $\tan\beta$  benchmark planes have been defined that are in agreement with the CDM and other low-energy constraints (see also Ref. [24]). From

a technical point of view, the NUHM introduces non-trivial relations between parameters, which thus cannot be scanned naively by independent loops. FeynHiggs 2.6 offers the new format of Parameter Tables to deal with such cases.

Input parameters can either be given in an input file (as in previous versions) or interpolated from a table, in almost any mixture. The table format is fairly straightforward:

MT	MSusy	MA0	TB	At	MUE ...
170.9	500	200	5	1000	761
170.9	500	210	5	1000	753
...					
170.9	500	200	6	1000	742
170.9	500	210	6	1000	735

For two given inputs (typically  $M_A$  and  $\tan\beta$ ) the four neighbouring grid points are searched in the table and the other parameters are interpolated from those points. An error is returned if the inputs fall outside of the table boundaries (i.e. no extrapolation).

The four predefined NUHM  $M_A$ - $\tan\beta$  planes [22] can be obtained from [www.feynhiggs.de/planes](http://www.feynhiggs.de/planes). The definition of new planes by the user is possible.

The Table concept is actually embedded into the new FeynHiggs Record. This is a data type which captures the entire content of a FeynHiggs parameter file. Using a Record, the programmer can process FeynHiggs parameter files independently of the frontend.

### 4 Output of FeynHiggs 2.6

We give a short overview of the output routines of the FeynHiggs library.

**FHHiggsCorr** – All Higgs-boson masses and mixings:  $M_{h_{1,2,3}}$ ,  $M_{H^\pm}$ ,  $\alpha_{\text{eff}}$ ,  $\text{UHiggs}$ ,  $\text{ZHiggs}$ .

**FHUncertainties** – Uncertainties of the masses and mixings.

**FHCouplings** – Couplings and Branching Ratios for the following Higgs decay channels:

$$\begin{aligned} h_{1,2,3} &\rightarrow f\bar{f}, \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg, & H^\pm &\rightarrow f^{(*)}\bar{f}', \\ &h_i Z^*, h_i h_j, H^+ H^-, & & h_i W^{\pm*}, \\ &\tilde{f}_i \tilde{f}_j, & & \tilde{f}_i \tilde{f}_j', \\ &\tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0, & & \tilde{\chi}_i^0 \tilde{\chi}_j^\pm, \end{aligned}$$

plus the corresponding channels of an SM Higgs with mass  $M_{h_i}$ :  $h_{1,2,3}^{\text{SM}} \rightarrow f\bar{f}, \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg$ .

**FHHiggsProd** – Higgs production-channel cross-sections (SM total cross-sections multiplied with MSSM effective couplings, see Ref. [25])

- $gg \rightarrow h_i$  – gluon fusion.
- $WW \rightarrow h_i, ZZ \rightarrow h_i$  – gauge-boson fusion.
- $W \rightarrow Wh_i, Z \rightarrow Zh_i$  – Higgs-strahlung.
- $b\bar{b} \rightarrow b\bar{b}h_i$  – bottom Yukawa process.
- $b\bar{b} \rightarrow b\bar{b}h_i$  – bottom Yukawa process, one  $b$  tagged.
- $t\bar{t} \rightarrow t\bar{t}h_i$  – top Yukawa process.

- $\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}h_i$  – stop Yukawa process.

**FHConstraints** – Electroweak precision observables, see e.g. Ref. [26] for details:

- $\Delta\rho$  at  $\mathcal{O}(\alpha, \alpha_s)$ , including NMFV effects.
- $M_W, \sin^2\theta_{\text{eff}}$  via SM formula +  $\Delta\rho$ .
- $\text{BR}(b \rightarrow s\gamma)$  including NMFV effects [27].
- $(g_\mu - 2)_{\text{SUSY}}$  including full one- and leading/sub-leading two-loop SUSY corrections.
- EDMs of electron (Th), neutron, Hg.

## 5 Download and Build

- Get the FeynHiggs tar file from [www.feynhiggs.de](http://www.feynhiggs.de).
- Unpack and configure:

```
tar xzf FeynHiggs-2.6.1.tar.gz
cd FeynHiggs-2.6.1
./configure
```

- “make” builds the Fortran/C++ part only.
- “make all” builds also the Mathematica part. The build takes about 3 min on a Pentium IV.
- “make install” installs the package.
- “make clean” removes unnecessary files.

The build was tested on Linux, Tru64 Unix, Mac OS, Windows (Cygwin) and also with Mathematica 6 (non-trivial due to its many incompatibilities) and older versions.

## 6 Usage

FeynHiggs has four modes of operation:

- Library Mode: Invoke the FeynHiggs routines from a Fortran or C/C++ program linked with **libFH.a**.
- Command-line Mode: Process parameter files in FeynHiggs or SLHA format from the shell prompt or in scripts with the **FeynHiggs** stand-alone executable.
- Web Mode: Interactively choose the parameters at the FeynHiggs User Control Center (FHUCC) and obtain the results on-line.
- Mathematica Mode: Access the FeynHiggs routines in Mathematica via MathLink with **MFeynHiggs**.

All programs and subroutines are documented in man pages.

### 6.1 Library Mode

The FeynHiggs library **libFH.a** is a static Fortran 77 library. Its global symbols are prefixed with a unique identifier to minimize symbol collisions. The library contains only subroutines (no functions), so that no include files are needed (except for the couplings) and the invocation from C/C++ is hassle-free. Detailed debugging output can be turned on at run time. All routines are described in detail in the API guide and on man-pages.

### 6.2 Command-line Mode

The user submits a parameter (text) file, such as

```
MT      170.9
MA0     200
TB       50
MSusy   975
Abs(M_2) 332
Abs(MUE) 980
Abs(At)  -300
Abs(Ab)  1500
Abs(M_3) 975
```

to the FeynHiggs executable with a command like

```
FeynHiggs file [flags]
```

where the *flags* are optional. The output is a human-readable version of the results. Details of this (rather voluminous) output are tagged with a % and can thus be masked off with

```
FeynHiggs file [flags] | grep -v %
```

The **table** utility converts the output to machine-readable format, for example

```
FeynHiggs file [flags] | table TB Mh0 > outfile
```

The new ‘**table**’ statement in the parameter file loads the table (see Sect. 3) and associates two interpolation variables with it. The changes are rather minimal:

Input File “table”		“inline table”			
MA0	200	MA0	200		
TB	50	TB	50		
table file.dat MA0 TB		table - MA0 TB			
		MA0	TB	At	MUE ...
		200	5	1000	761
		210	5	1000	753
		...			

Loops over parameter values (parameter scans) are possible as in former versions:

- MA0 200 400 50, linear: 200, 250, 300, 350, 400,
- TB 5 40 \*2, logarithmic: 5, 10, 20, 40,
- TB 5 50 /6, number of steps: 5, 14, 23, 32, 41, 50.

### 6.3 SUSY Les Houches Accord Format

The **FeynHiggs** executable can also process files in SUSY Les Houches Accord 2 (SLHA2) format [28]. It uses the SLHA Library [29]. Processing of SLHA2 files can also be done in Library Mode with the subroutine **FHSetSLHA**.

FeynHiggs in fact tries to read each file in SLHA format first and if that fails, falls back to its native format.

### 6.4 Web Mode

The FeynHiggs User Control Center (FHUCC) is on-line at [www.feynhiggs.de/fhucc](http://www.feynhiggs.de/fhucc). It is a Web interface for the command-line frontend. The user gets the results together with the input file for the command-line frontend. A screen-shot is shown in Fig. 3.

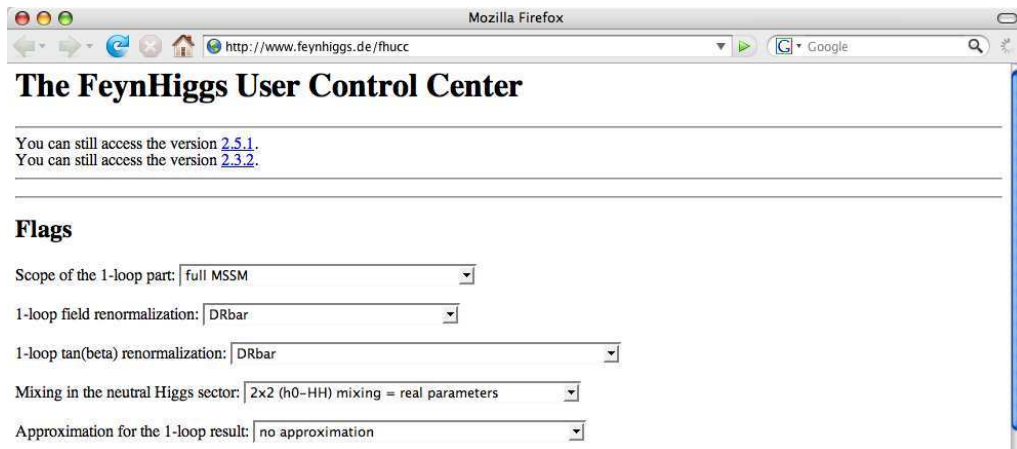


Fig. 3. Screen-shot from [www.feynhiggs.de/fhucc](http://www.feynhiggs.de/fhucc).

## 6.5 Mathematica Mode

A more powerful interactive environment is provided by the Mathematica interface of FeynHiggs. The Math-Link executable `MFeynHiggs` must first be loaded with

```
Install["MFeynHiggs"]
```

and makes all FeynHiggs routines available as Mathematica functions. In combination with the arsenal of standard Mathematica functions such as `ContourPlot` and `Manipulate`, even sophisticated analyses can be carried out easily.

## 7 Summary: Main New Features

Version 2.6 of FeynHiggs introduces the following new features:

- Higgs masses are computed as the real part of the complex pole.
- Two kinds of ‘mixing’ matrices with different properties (`UHiggs`, `ZHiggs`) are returned. The user can choose which mixing matrix to use in all Higgs production and decay channels (default: `ZHiggs`).
- Inclusion of the full cMSSM two-loop  $\mathcal{O}(\alpha_t \alpha_s)$  corrections in highly optimized form.
- Inclusion of full one-loop NMFV effects.
- Possibility to interpolate parameters from data tables. Availability of  $M_A$ – $\tan \beta$  planes in agreement with CDM constraints.
- Total Higgs production cross-sections in effective coupling approximation
- EDMs of electron (Th), neutron, Hg.

## References

1. R. Peccei, H. Quinn, *Phys. Rev. Lett.* **38** (1977) 1440; *Phys. Rev.* **D16** (1977) 1791.
2. S. Dimopoulos, S. Thomas, *Nucl. Phys.* **B465** (1996) 23 [hep-ph/9510220].
3. S. Heinemeyer, W. Hollik, G. Weiglein, *Comput. Phys. Comm.* **124** (2000) 76 [hep-ph/9812320]. The FeynHiggs Web site is at [www.feynhiggs.de](http://www.feynhiggs.de).
4. S. Heinemeyer, W. Hollik, G. Weiglein, *Eur. Phys. J.* **C9** (1999) 343 [hep-ph/9812472].
5. G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. Weiglein, *Eur. Phys. J.* **C28** (2003) 133 [hep-ph/0212020].
6. M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, *JHEP* **0702** (2007) 047 [hep-ph/0611326].
7. A. Pilaftsis, *Phys. Rev.* **D58** (1998) 096010 [hep-ph/9803297]; *Phys. Lett.* **B435** (1998) 88 [hep-ph/9805373]; D. Demir, *Phys. Rev.* **D60** (1999) 055006 [hep-ph/9901389]; S. Choi, M. Drees, J. Lee, *Phys. Lett.* **B481** (2000) 57 [hep-ph/0002287]; A. Pilaftsis, C. Wagner, *Nucl. Phys.* **B553** (1999) 3 [hep-ph/9902371]; M. Carena, J. Ellis, A. Pilaftsis, C. Wagner, *Nucl. Phys.* **B586** (2000) 92 [hep-ph/0003180]; T. Ibrahim and P. Nath, *Phys. Rev.* **D63** (2001) 035009 [hep-ph/0008237]; *Phys. Rev.* **D66** (2002) 015005 [hep-ph/0204092]; S. Heinemeyer, *Eur. Phys. J.* **C22** (2001) 521 [hep-ph/0108059].
8. S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, *Phys. Lett.* **B652** (2007) 300 arXiv:0705.0746 [hep-ph].
9. A. Brignole, G. Degrassi, P. Slavich, F. Zwirner, *Nucl. Phys.* **B631** (2002) 195 [hep-ph/0112177].
10. A. Brignole, G. Degrassi, P. Slavich, F. Zwirner, *Nucl. Phys.* **B643** (2002) 79 [hep-ph/0206101].
11. A. Dedes, G. Degrassi, P. Slavich, *Nucl. Phys.* **B672** (2003) 144 [hep-ph/0305127].
12. S. Heinemeyer, W. Hollik, F. Merz, S. Peñaranda, *Eur. Phys. J.* **C37** (2004) 481 [hep-ph/0403228].
13. T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, arXiv:0709.1907 [hep-ph].
14. T. Hahn, physics/0607103.
15. M. Frank, S. Heinemeyer, W. Hollik, G. Weiglein, hep-ph/0202166.
16. A. Freitas and D. Stöckinger, *Phys. Rev.* **D66** (2002) 095014 [hep-ph/0205281].



17. W. Hollik, H. Rzehak, *Eur. Phys. J.* **C32** (2003) 127 [hep-ph/0305328].
18. S. Heinemeyer, W. Hollik, G. Weiglein, *Eur. Phys. J.* **C16** (2000) 139 [hep-ph/0003022].
19. J. Küblbeck, M. Böhm, A. Denner, *Comput. Phys. Comm.* **60** (1990) 165;  
T. Hahn, *Comput. Phys. Comm.* **140** (2001) 418 [hep-ph/0012260].
20. T. Hahn, C. Schappacher, *Comput. Phys. Comm.* **143** (2002) 54 [hep-ph/0105349].
21. M. Carena, S. Heinemeyer, C. E. M. Wagner, G. Weiglein, *Eur. Phys. J.* **C26** (2003) 601 [hep-ph/0202167]; *Eur. Phys. J.* **C45** (2006) 797, [hep-ph/0511023].
22. J. Ellis, T. Hahn, S. Heinemeyer, K. Olive, G. Weiglein, to appear in *JHEP*, arXiv:0709.0098 [hep-ph].
23. J. Ellis, K. Olive, Y. Santoso, *Phys. Lett.* **B539** (2002) 107 [hep-ph/0204192];  
J. Ellis, T. Falk, K. Olive, Y. Santoso, *Nucl. Phys.* **B652** (2003) 259 [hep-ph/0210205];  
M. Olechowski, S. Pokorski, *Phys. Lett.* **B344** (1995) 201 [hep-ph/9407404]; V. Berezinsky, A. Bottino, J. Ellis, N. Fornengo, G. Mignola, S. Scopel, *Astropart. Phys.* **5** (1996) 1 [hep-ph/9508249];  
M. Drees, M. Nojiri, D. Roy, Y. Yamada, *Phys. Rev.* **D56** (1997) 276 [Erratum – ibid. **D64** (1997) 039901] [hep-ph/9701219];  
M. Drees, Y. Kim, M. Nojiri, D. Toya, K. Hasuko, T. Kobayashi, *Phys. Rev.* **D63** (2001) 035008 [hep-ph/0007202];  
P. Nath, R. Arnowitt, *Phys. Rev.* **D56** (1997) 2820 [hep-ph/9701301];  
A. Bottino, F. Donato, N. Fornengo, S. Scopel, *Phys. Rev.* **D63** (2001) 125003 [hep-ph/0010203];  
S. Profumo, *Phys. Rev.* **D68** (2003) 015006 [hep-ph/0304071];  
D. Cerdeno, C. Muñoz, *JHEP* **0410** (2004) 015 [hep-ph/0405057];  
H. Baer, A. Mustafayev, S. Profumo, A. Belyaev, X. Tata, *JHEP* **0507** (2005) 065 [hep-ph/0504001].
24. J. Ellis, S. Heinemeyer, K. Olive, A.M. Weber, G. Weiglein, *JHEP* **0708** (2007) 083 arXiv:0706.0652 [hep-ph].
25. T. Hahn, S. Heinemeyer, F. Maltoni, G. Weiglein, S. Willenbrock, [hep-ph/0607308], The SM cross-sections are taken from the Web site maltoni.home.cern.ch/maltoni/TeV4LHC, providing also a comprehensive list of original references.
26. S. Heinemeyer, W. Hollik, G. Weiglein, *Phys. Rept.* **425** (2006) 265 [hep-ph/0412214].
27. T. Hahn, W. Hollik, J.I. Illana, S. Peñaranda, hep-ph/0512315.
28. P. Skands et al., *JHEP* **0407** (2004) 036 [hep-ph/0311123];  
B. Allanach, et al., hep-ph/0602198.
29. T. Hahn, hep-ph/0408283; hep-ph/0605049.